Skin temperature and vigilance: from association to application

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2013

Correlated fluctuations of daytime skin temperature and vigilance

Based on:

Romeijn N, Van Someren EJ (2011) Correlated fluctuations of daytime skin temperature and vigilance *J Biol Rhythms* 26:68-77.

Abstract

Skin temperature shows spontaneous ultradian fluctuations during everyday-life wakefulness. Previous work showed that mild manipulations of skin temperature affect human sleep and vigilance, presumably by influencing neuronal systems involved in both thermal sensing and arousal regulation. We therefore examined whether fluctuations in skin temperature are associated with those in vigilance level under conditions similar to everyday-life situations requiring sustained attention.

Eight healthy participants (30.1 ± 8.1 years, mean ± SD) participated in a two-day protocol during which vigilance and skin temperature were assessed 4 times per day in a silent dimly-lit, temperature-controlled room. Vigilance was assessed by measuring reaction speed and lapses on a novel sustained vigilance task, specifically designed to increase lapse rate and the range of reaction times. Skin temperature was sampled at 30-second intervals from 3 locations: distal, intermediate and proximal temperatures were obtained from the middle finger (T_{finger}), the wrist (T_{wrist}) and the infraclavicular area (T_{chest}), respectively. Furthermore, three distal-to-proximal gradients (DPGs) were calculated. Mixed-effect regression analyses were used to evaluate the association of the fluctuations in temperatures and gradients and those in response speed and lapse probability.

Especially the spontaneous fluctuations in proximal temperature were negatively associated with fluctuations in response speed, and positively with lapse rate. If individual T_{chest} temperature ranges were classified into ten deciles, they accounted for 23% of the variance in response speed and for 11% of the variance in lapse rate.

The findings indicate coupling between the spontaneous within-session fluctuations in skin temperature and vigilance during the day, and are compatible with the hypothesis of overlap in brain networks involved in the regulation of temperature and vigilance. From an applied point of view, especially proximal skin temperature assessment may be of use in vigilance monitoring.

Introduction

Temperatures of different areas of the human body show pronounced 24-hour rhythms. While the core body temperature rhythm received most attention in circadian research, the 24-rhythm in skin temperature may be at least as pronounced. In addition to the marked 24-hour rhythms, temperature fluctuations in the ultradian frequency range can be quite marked, especially for skin temperatures (Van Marken Lichtenbelt et al., 2006). Such fluctuations, rather than fixed levels, are typical of most physiological and behavioral processes (Hu et al., 2009), and may in case of body temperature reflect the multiple feedback, feedforward, and open-loop components that contribute to thermal balance around a 'balance point' rather than a set point (Romanovsky, 2007).

Several findings suggest that sleepiness and vigilance are closely linked to these skin temperature fluctuations in the thermoneutral range (Fronczek et al., 2006; Fronczek et al., 2008b; Krauchi, 2007; Raymann et al., 2005, 2008; Raymann & Van Someren, 2007). Thermosensitive neurons involved in sleep regulation in the pre-optic area and anterior hypothalamus (POAH) and other brain areas have been proposed to be involved in this relationship (Van Someren, 2006). Spontaneous changes in the activity level of these neurons would presumably result in simultaneous, and therefore correlated, changes in sleep propensity and in skin vasodilation and consequently skin temperature. It has even been proposed that experimental activation of these thermosensitive neurons by a mild increase in skin temperature – insufficient to alarm the thermoregulatory mechanisms – could enhance sleep propensity (Van Someren, 2000). Initial studies indeed showed correlations between skin temperature and sleep onset latency (Fronczek et al., 2006; Gradisar & Lack, 2004; Kräuchi et al., 1999, 2000). Subsequently, a causal contribution of skin temperature to arousal regulating mechanisms was demonstrated by controlled studies in which skin temperature was subtly manipulated while measuring sleep onset latency via multiple sleep latency tests (MSLT) (Raymann et al., 2005), sleep onset latency via multiple maintenance of wakefulness tests (MWT) (Fronczek et al., 2008a), sleep depth via polysomnography (PSG) (Fronczek et al., 2008b; Raymann et al., 2008), or vigilance performance as measured via the psychomotor vigilance task (Raymann & Van Someren, 2007).

To the best of our knowledge, no previous study addressed the possible contribution the assessment of spontaneous fluctuations in skin temperature could make in estimating the risk of lapses of vigilance and long reaction times. In addition to the value for our understanding of the brain mechanisms of ultradian variation in vigilance level, such risk estimates are of great societal interest: Industrial catastrophes, transportation accidents, and medical errors have been suggested to result from lapses of attention that occur when sleep-deprived individuals fail to stay alert while fighting the tendency to fall asleep (Barger et al., 2006; Connor

et al., 2002; Mitler et al., 1988; Philip & Akerstedt, 2006). The establishment of valid behavioral and physiological estimates of the risk of lapses in attention could eventually lead to warning systems and thus contribute to the prevention of their disastrous consequences.
We therefore performed a study on the value of skin temperature in estimates of the risk of lapses and long reaction times in a vigilance task under conditions that are close to everyday-life situations that require sustained attention.

Methods

All procedures complied with the declaration of Helsinki and medical ethical approval was obtained from the medical ethical committee of the VU University medical center.

Participants

Eight healthy participants (30.1 ± 8.1 years of age, mean ± standard deviation (SD), 5 male (range: 22-47 years), 3 female (range: 28-30 years)) recruited from within the institute participated in a two-day experimental protocol. None of them had any known history of sleep-related disorders. Age was not used as a selection criterion, in order to allow findings to be generalized to a larger population. Since the protocol was meant to simulate everyday-life situations, caffeine intake was semi-controlled by instructing participants to keep the quantity and time of caffeine intake equal for both days of the experiment. Adherence was verified from logs kept by the participants. No instructions were given with regards to sleeping pattern. Subjective sleep behavior, as measured by self-reported bedtime, number of wake bouts, and total time awake after sleep onset, was logged as well. Using 100mm Visual Analog Scales, subjects were interrogated on several sleep related parameters, of which we here report self-rated sleep quality, rated between 0mm (very bad) and 100mm (very good).

Procedure

A schematic overview of the experimental procedure can be seen in figure 1. The procedure spanned two days with an interday interval of 0-4 days, depended on availability of the participant and acquisition room. Vigilance assessments were done on two separate days to increase the amount of data points for analysis. Each experimental day consisted of 4 sessions of vigilance assessment at fixed 2h intervals, with the first session starting between 09.00-11.00. Intersession intervals were standardized within subjects. Inbetween the assessment sessions, participants were allowed to continue their daily activities consisting of indoor office work under lighting conditions of 288 ± 48 lux (mean ± SD, similar for all subjects).

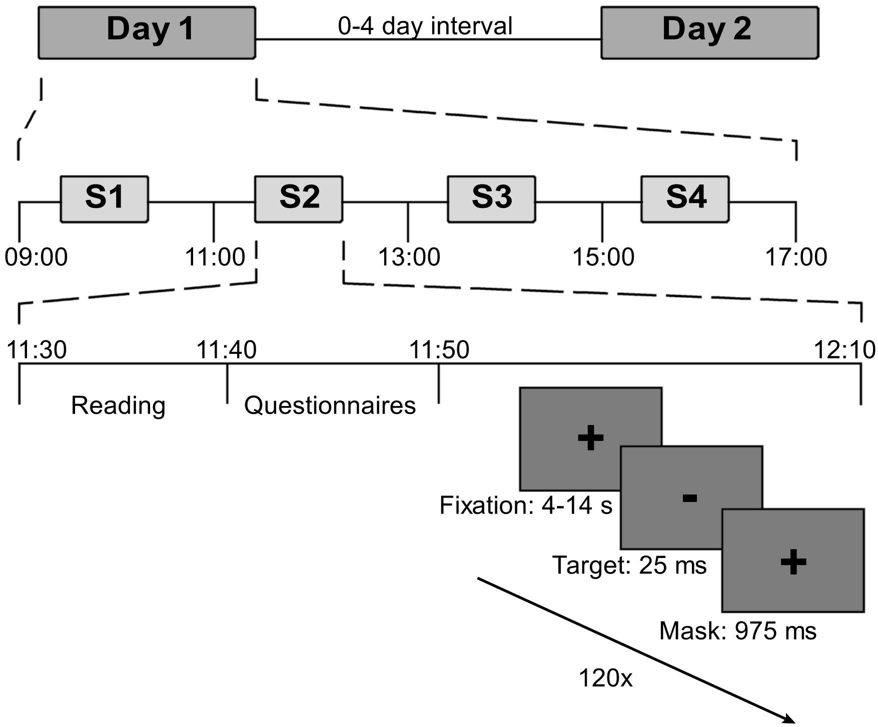

Figure 1 Schematic overview of the experimental protocol. During each day of the 2-day protocol (0-4 day interval), 4 vigilance assessment sessions (S1-S4) were run at 2h intervals. Each session consisted of a 10 minute acclimatization period of quiet reading, followed by a 10 minute computerized questionnaire, and a 19 minute brief stimulus reaction time task.

During each session, participants were seated in front of a computer laptop in a dimly-lit room (15 lux measured at the eyes in gaze direction) at an environmental temperature of 22.6 ± 1.2 °C (mean ± SD). To assess skin temperature, temperature loggers were attached to the participant, as described below. Each session started with an acclimatization period, in which the participant was asked to sit still and read material of own choice for 10 minutes.

After this 10 minute acclimatization period, a computerized questionnaire and task battery was presented. The first ten minutes consisted of questions, of which we here report only the Karolinska Sleepiness Scale (KSS, Akerstedt & Gillberg, 1990), used to assess subjective sleepiness. Subsequently, participants were presented with a 19 minute sustained attention task, described below. This task was rehearsed once by every subject prior to the start of the experiment.

Brief Stimulus Reaction Time Task (BSRT)

Sustained attention tasks, of which the most familiar may be the psychomotor vigilance task (PVT, Dinges & Powell, 1985) have shown to be of value for vigilance monitoring in numerous studies. Several other simple and more complex reaction time tasks have successfully been applied, for example to demonstrate subtle abnormalities in vigilance in insomnia (Altena et al., 2008). For the present study, we designed a novel sustained attention task with the specific aim to increase the likelihood of lapses as well as the range and average of reaction times, thus better allowing for subtle fluctuations in vigilance that occur even during rested conditions (Peiris et al., 2006). As compared to the PVT, our Brief Stimulus Reaction Time Task (BSRT) has a longer duration (PVT: 10 min, BSRT: 19 min); a shorter stimulus presentation duration (PVT: maximally 999ms, BSRT: 25ms); relatively long interstimulus intervals (PVT: 1-10s, BSRT: 4-14s); a small stimulus size; and a low contrast between the stimulus and fixation cross. Participants were instructed to fixate at a black crosshair ('+' sign), displayed against a gray background, and to respond as fast as possible if they saw the fixation cross change into a hyphen ('-'), by pressing a button with the index finger of their dominant hand. The change into a hyphen lasted only 25 ms and occurred after a random interval lasting between 4 and 14 seconds (84 ms step resolution). Reaction times (RT) were recorded in milliseconds. A lapse was recorded if participants did not respond within 500 ms. The task comprised 120 stimuli and lasted for 19 minutes per session.

Skin temperature

Skin temperature was assessed using iButtons (type DS1922L, MAXIM/Dallas), set to wirelessly acquire temperature samples at 30 second intervals with a resolution of .0625°C. The method has previously been validated and described in detail (Van Marken Lichtenbelt et al., 2006). On average, the accuracy bias in a batch of comparable iButtons previously tested was -0.09 °C. Any calibration and rescaling to further reduce this small bias would not affect the outcomes in any way, because all reported results are within subject, as described below.

Skin temperature was measured at three locations. Distal temperature was obtained from the dorsal side of the base of the middle finger (T_{finger}). Proximal temperature was obtained from the infraclavicular area on the chest (T_{chest}). The dorsal side of the wrist was chosen as a third site that may – depending on the conditions – represent both proximal and distal skin temperature (T_{wrist}) (Aschoff & Wever, 1958). The iButtons were affixed with adhesive tape (Fixomull stretch, BSN medical GmbH, Germany) on the side of the non-dominant hand in order to exclude any interference with motor responses during the task. It has previously been suggested that the gradient between temperatures measured at two locations, one distal and the other more proximal skin, has a strong association with sleep propensity (Kräuchi et al., 1999). We therefore calculated three gradients of relative distal to relative proximal temperature: Distal-to-proximal gradient of finger minus wrist (DPG_{f-w}), finger minus chest (DPG_{f-c}) and wrist minus chest (DPG_{w-c}).

Data analysis
In order to obtain a normal distribution for the recorded responses, the inverse of reaction times was taken, denoted as ‘speed’ (sec^{-1}). For every single stimulus a corresponding last temperature readout is present. The hypothesis of our interest is whether the momentary skin temperature value has predictive value for the response to the stimulus, i.e. for reaction speed and the risk of a lapse to occur. To do so, we applied mixed effect linear regression analyses to estimate the effect of the three temperatures and three temperature gradients as regressors for reaction speed. Likewise, mixed effect logistic regression analyses were performed to evaluate the effect of the temperatures and their gradients as regressors for lapse probability. Mixed effect analyses were performed using the MLwiN software package (Institute of Education, London, UK) and data were structured according to their four-level hierarchical dependency, i.e. individual stimulus-responses nested within four sessions nested within two days, again nested within eight participants (Petkova & Teresi, 2002; Twisk, 2003).

Visualization of the relationship between performance and temperatures
The temperature measured over the 8 sessions fluctuated both within and between sessions. Moreover, ranges differed considerably between participants. In order to still be able to visualize the predictive value of within-subject temperature fluctuations for their performance fluctuations, we took the following approach. For each of the six temperature and gradient variables, the range of values of each individual participant was classified into ten deciles, each representing one tenth of the total amount of temperature measurements, acquired during the 2*4*19 minutes of task performance.

For each temperature decile range, the average temperature, reaction speed and percentage of lapses were calculated over all time points where temperatures were measured that belonged to that specific decile of an individual’s temperature range. For graphical purposes, averages and standard errors were calculated over subjects for each decile and plotted. Plotting temperature and performance data averaged in deciles was necessary because both variables show considerable between-subject differences in their average and range. The procedure concerned visualization only, not statistical testing because mixed-effect analysis regards between-subject differences as random variability, and effects reported are to be interpreted as within-subject effects (Twisk, 2003).

Secondary analyses
A critical evaluation of the possible value of skin temperature as a contributive factor for the assessment of reaction speed and lapse probability includes testing of redundancy. Notable, it has previously been found that performance can covary

with subjective sleepiness and with time-of-day – the latter unlikely due to learning but rather due to circadian modulation (Dinges et al., 1994; Raymann & Van Someren, 2007; Van Dongen & Dinges, 2005). If skin temperature would covary with performance in a similar way as subjective sleepiness or time-of-day covary with performance, it would in practical applications for vigilance prediction be easier to use the latter variables because they are much easier to record than skin temperature. In that scenario the possible value of skin temperature monitoring for applications would be limited to those situations where information on subjective sleepiness or time-of-day are not readily available.

We therefore evaluated, once more applying mixed effect regression analysis, the effect of subjective sleepiness and time-of-day on the three temperature variables and three temperature gradient variables as well as on reaction speed. Likewise, mixed effect logistic regression analysis was performed to evaluate the effect of time-of-day on lapse probability. Furthermore, mixed effect regression analysis was used to assess possible differences in measured response speed and lapse probability between day 1 and 2.

Results

On average, participants reported to have slept 06:45 ± 01:19 (hh:mm, mean± SD) prior to assessment days, with sleep quality being reported as 61.1 ± 25.4 (mean ± SD) on a scale with 0 representing very bad and 100 very good. Furthermore, participants had an average coffee consumption of 1.4 ± 0.9 (mean ± SD, range: 0-3) cups of coffee per day. One of the 8 participants refrained from caffeine consumption, while the remaining 7 kept their caffeine intake fixed in both time and amount for both measurement days.

Grand averages of the measured temperatures and temperature gradients are shown in table 1a. The overall response speed was 2.68 ± 0.08 (mean ± standard error of the mean), corresponding to reaction times fluctuating around 373 milliseconds. Overall, lapses occurred with a probability of 0.25 (95% Confidence Interval, CI: 0.17-0.39).

Response speed was strongly dependent on the last temperature value measured prior to stimulus presentation. Table 1b shows regression coefficient estimates (effects), the standard error of the estimate, the z-statistic of the estimated effect and its p-value. Chest temperature was the most significant regressor; for every degree Celsius T_{chest} increased, response speed decreased by 0.18 s^{-1}, a decrease of about 7%, corresponding to an increase in reaction time of 27 ms.
Smaller and similarly negative coefficients were found for T_{finger}, DPG_{f-w}, and DPG_{f-c}. A small positive coefficient was found for DPG_{w-c}.

	a) **Temperature (°C)**	b) **Effect on speed (s^{-1}/ °C)**			c) **Effect on lapse (Odds Ratio / °C)**			
Signal	**Mean ± s.e.m.**	**Effect ± s.e.m.**	**z-value**	**p-value**	**O.R.**	**95%CI**	**z-value**	**p-value**
T_{chest}	35.23 ± 0.02	-0.18 ± 0.03	-7.32	0.000	1.76	1.35-2.31	4.15	0.000
T_{finger}	31.57 ± 0.48	-0.03 ± 0.01	-5.67	0.000	1.09	1.03-1.16	3.10	0.002
T_{wrist}	32.04 ± 0.33	0.00 ± 0.01	0.30	0.764	1.13	1.01-1.25	2.20	0.028
DPG_{f-c}	-3.66 ± 0.46	-0.02 ± 0.01	-4.00	0.000	1.07	1.01-1.13	2.23	0.026
DPG_{f-w}	-0.48 ± 0.21	-0.05 ± 0.01	-6.86	0.000	1.09	1.02-1.17	2.42	0.016
DPG_{w-c}	-3.18 ± 0.32	0.04 ± 0.01	3.27	0.001	1.03	0.93-1.15	0.59	0.556

Table 1 Mean skin temperature and the effects of fluctuations in skin temperature on speed and lapses.

(a) Mean temperature and standard errors of the 4 sessions of the two days of the middle finger (T_{finger}), the infraclavicular area on the chest (T_{chest}) and the wrist (T_{wrist}), as well as the calculated three gradients of relative distal to relative proximal temperature: finger minus wrist (DPG_{f-w}), finger minus chest (DPG_{f-c}) and wrist minus chest (DPG_{w-c}).

(b) Results of the mixed effect regression analyses, indicating effects of temperature fluctuations as regressor for fluctuations in response speed, in 1/sec per ˚C change in temperature. The regression model was as follows: $Speed_{ijkl} = ß0_{ijkl} + ß1 * X_{ijkl}$ (subscripts indicate *i*th observation in the *j*th session on day *k* for subject *l*). with X representing either T_{chest}, T_{finger}, T_{wrist}, DPG_{f-c}, DPG_{f-w}, or DPG_{w-c}.

(c) Results of the mixed effect regression analyses, indicating effects of temperature fluctuations as regressor for fluctuations in lapse probability (Odds Ratio per ˚C change in temperature). 95% Confidence intervals for the Odds Ratio are shown as well. The logistic regression model was as follows: $Logit(P(lapse)_{ijkl}) = ß0_{ijkl} + ß1 * X_{ijkl}$ (subscripts indicate *i*th observation in the *j*th session on day *k* for subject *l*) with P representing the probability and X representing either T_{chest}, T_{finger}, T_{wrist}, DPG_{f-c}, DPG_{f-w}, or DPG_{w-c}.

The probability of lapses increased strongly with increasing values of the last temperature measured prior to stimulus presentation. Table 1c shows the odds ratios and confidence intervals for the predictive value of temperatures for lapses to occur. Chest temperature was by far the most significant regressor. The odds ratio was 1.76 (95% CI: 1.35-2.31) per degree Celsius increase of T_{chest}. Smaller and similarly positive odds ratios were found for T_{finger}, T_{wrist}, DPG_{f-w}, and DPG_{f-c}. No effect was found for DPG_{w-c}.
Temperatures showed considerable between-subject variation. The intraclass correlation coefficients, i.e. the proportions of variance as estimated from the mixed effect model were as follows. For chest temperature, between-subject differences accounted for 51% of the total variance; between-day differences for 10%, time-of day differences for 35%, leaving 4% residual error variance. For finger temperature, between-subject differences accounted for 26% of the total variance; between-day differences for 0%, time-of day differences for 68%, leaving 6% residual error variance. For wrist temperature, between-subject differences accounted for 31% of the total variance; between-day differences for 17%, time-of day differences for 51%, leaving 2% residual error variance.

Visualization of the relationship between performance and temperatures
Figure 2 shows that higher infraclavicular temperatures are indicative for worse performance as indicated by decreasing speed and increasing lapse probability. When calculated over the performance and temperature decile means, knowledge of the chest temperature decile reduces the uncertainty on response speed by 23%. Similarly, knowledge on the chest temperature decile accounts for 11% of the variance in lapse rate means. The same relationship, but less pronounced was seen for finger temperature. Wrist temperature showed some value as indicator of lapse probability, but not as indicator of response speed.

Results Secondary analyses
We next evaluated whether skin temperature was still associated with vigilance performance after accounting for the possible predictive power of other variables that may be easier to access. Neither reaction speed nor lapse probability could be predicted in any significant way by the most recent KSS subjective sleepiness rating the participants gave (p=0.88 and p=0.51 respectively). Reaction speed was not significantly modulated by time-of-day (1st order term p=0.64; 2nd order term p=0.23). Also the probability of a lapse to occur was not significantly modulated by time-of-day (1st order term p=0.59; 2nd order term p=0.79). Thus, the lack of predictive value of the KSS and time-of-day for performance exclude these variables as possibly overlapping with the predictive value of skin temperature. Also, these findings corroborate earlier findings that learning effects on vigilance tasks are negligible if not absent.
With regard to systematic differences between day one and two, neither reaction speed nor lapse probability could be predicted in any significant way by the day on which measurements were done (p=0.65 and p=0.40 respectively).

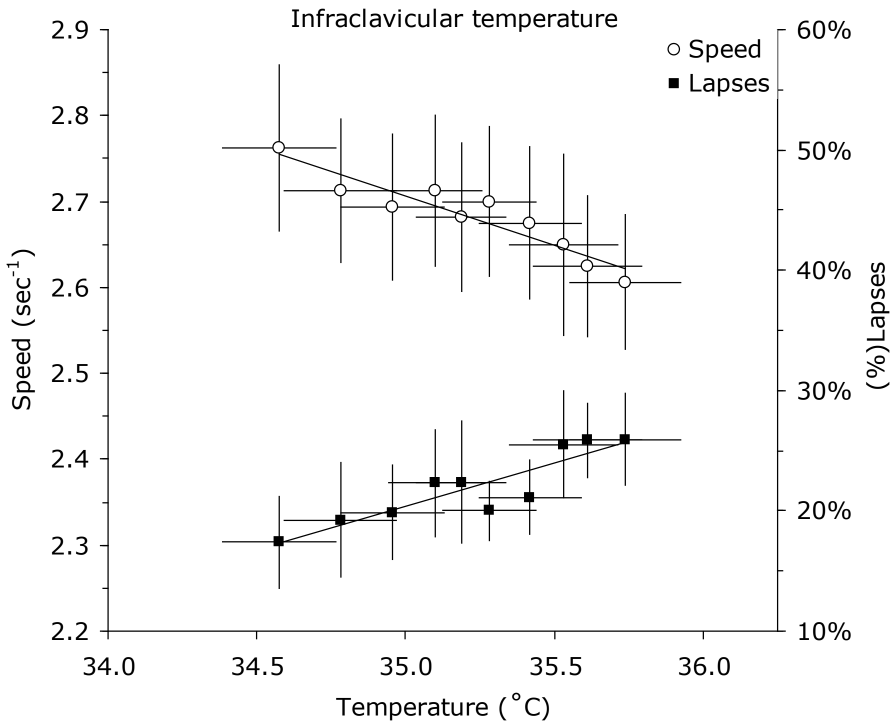

Figure 2 Figure 2 plots the average speed (open circles) and percentage of lapses (closed squares) over the ten deciles of infraclavicular temperature. Vertical error bars indicate the between-subject standard error of the mean for the performance measures. Horizontal error bars indicate the standard error of the mean for the between-subject variation in the range associated with each of the ten temperature percentiles. Linear regression lines are given. Note that all analyses have been done on raw data; deciles have only been used to graphically illustrate the relationship. The reason for plotting temperature and performance data averaged in deciles is that both variables show considerable between-subject differences in their average and range.

Discussion

We demonstrated that skin temperature is of value in the assessment of the risk of lapses and long reaction times in a novel vigilance task under conditions that are close to everyday-life situations that require sustained attention. Of the three sites assessed, proximal skin temperature measured at the infraclavicular area on the chest was most valuable for estimating both reaction speed and the risk of lapses, with high skin temperature associated with low speed and high lapse probability. These findings are consistent with several previous correlational and experimental studies which showed that especially the proximal skin temperature is correlated with – and when manipulated, causally affects – vigilance (Raymann & Van Someren, 2007), sleep onset latency (Fronczek et al., 2006; Raymann et

al., 2005), and sleep depth (Fronczek et al., 2008b; Raymann et al., 2008).
It is important to note that the word ‘causally’ used here refers to the fact that manipulating an independent variable (skin temperature) robustly and across multiple experiments altered a dependent output variable (in this case either vigilance or sleep onset latency), while the underlying mechanism remains to be demonstrated.

Of secondary value in the estimation of reaction speed, and contributing to the ability to assess vigilance in addition to chest temperature, was the gradient of finger temperature to wrist temperature. This gradient has been proposed to provide insight into peripheral vasoconstriction, since it measures the difference between the temperature of a distal skin area rich in arteriovenous anastomoses and a more proximal site lacking them, while exposed to the same environmental temperature. Our gradient is similar to that of Rubinstein *et al*. who showed that the gradient between finger and forearm is an accurate measure of the peripheral vasoconstriction that is controlled by the sympathetic branch of the autonomic nervous system (Rubinstein & Sessler, 1990).
Previous literature showed a correlation between peripheral vasoconstriction and sleep onset latency (Fronczek et al., 2006; Kräuchi et al., 1999). While sleep propensity, of which sleep onset latency is a measure, is not to be confused with performance, our current data combined with earlier findings could suggest that peripheral vasoconstriction could be an index of both sleep propensity and performance.
Of note, the findings appear to be robust and suggest practical applicability in everyday life, because they were obtained under conditions that are close to everyday-life operational control situations and participants were allowed to continue their daily activities between test sessions.
The variance in vigilant performance accounted for by skin temperature measurements is too limited to envision stand-alone application. It may be however that skin temperature adds value to multivariate systems for vigilance assessment, besides e.g. core body temperature, electroencephalography, pupil diameter, eye-blink rate and, in some operational control situation, behavioral measures such as weaving in case of car driving.
For daytime vigilance assessment, redundancy of skin temperature and core temperature, as variables that predict vigilance, is unlikely. Although core body temperature and skin temperature measured under field conditions are inversely correlated if assessed over one or more 24-hour periods, this is unlikely to be the case during the office hours assessed in our study. While skin temperature fluctuates considerably during daytime, core body temperature shows a plateau with, due to inertia, little fluctuations within a small range that is usually close to the resolution of temperature sensors (Van Marken Lichtenbelt et al., 2006). This is in fact the major reason for determining the temperature minimum instead of the temperature maximum in studies on its circadian rhythm.
Also, it remains to be evaluated to what circumstances our findings can be

generalized. In the present study participants did office work at relatively constant temperature levels. It seems less likely that reliable estimates can be obtained in highly variable or extreme thermal environments. While the issue of measuring vigilance in temperature instable environments still needs to be addressed in future studies, one may hypothesize that both T_{chest} and $DPG_{f\text{-}w}$ will show some robustness in cases where temperature fluctuates within certain limits. The infraclavicular sensor is covered by clothing, resulting in a microclimate between skin and clothing, thereby dampening changes in environmental temperature and attenuating their effect on skin temperature at this site of the body. This microclimate argument does not apply to either T_{wrist} or T_{finger}, but since the DPG measures the difference between both locations, and both locations are equally exposed to environmental changes, the distal to proximal gradient might be relatively robust as well.
For now however, the data suggests that at least in environments of relatively constant temperature, skin temperature can be of some value in the assessment of vigilance, which is a valuable finding in itself considering that many vigilance-demanding process-control situations take place within temperature-stable indoor environments.
Ancillary analysis revealed no systematic effects of time of day on reaction speed or probability of lapses. It must be noted though, that our protocol was not specifically designed to evaluate correspondence of systematic diurnal variations in skin temperature and vigilance, but rather to focus on nonsystematic fluctuations in vigilance and temperature within a session. This limitation is inherent to measurements during office hours, which do not provide a complete view of 24-hour periods in temperature and vigilance. Therefore, a study on correspondence in diurnal rhythms would require a different protocol.
Since our protocol surveyed vigilance during office hours after a normal sleep history, the current findings are of applied value for those circumstances where optimal vigilance is essential for operational control. The question whether skin temperature can aid in the estimation of more severe fluctuations in vigilance as result of sleep deprivation remains to be addressed in future studies. This issue was already touched upon by Miro et al.(Miro et al., 2002), who showed that in a 48h protocol of total sleep deprivation, skin temperature was correlated to vigilance. However, in this study temperature was sampled once every two hours, thereby foregoing the possible additive information that the minute-by-minute fluctuations in skin temperature can provide as a measure of vigilance.
With regards to previous literature (Van Marken Lichtenbelt et al., 2006) one might pose that the response time of the iButtons might be too slow to recover from drastic temperature changes that participants could possibly experience in between testing sessions. However, in the Van Marken Lichtenbelt paper a difference of up to 1 °C occurred between a thermocouple and an iButton only temporarily and only in case of being transferred to an extremely cold environment. In our study participants stayed indoors in agreeable and constant environmental thermal conditions in between test sessions; moreover, for iButtons worn on the

skin under clothes the difference between skin temperature and environmental temperature is minimal due to the microclimate induced.
The iButton has a time constant of 19 seconds and can theoretically change by more than 10 °C over subsequent 30-second intervals (Van Marken Lichtenbelt et al., 2006). However, when applied to the skin, heat transfer does not reach its theoretical maximum and its response is slower than that of small thermocouples. It is thus well possible that thermal inertia has introduced a bias towards a lower predictive value of skin temperature on vigilant performance than would be the case with sensors that track skin temperature fluctuations even more accurately. In order to get an indication of this possibility, we performed ancillary analyses and evaluated the time lag at which skin temperature and vigilance were maximally associated in ancillary cross-correlation analyses with lags of up to ten minutes. For reaction speed, taking the chest temperature measured 0.5 minutes earlier than the last preceding temperature assessment slightly (2%) increased the magnitude of the regression coefficient. For other temperatures and gradients, no improvement in the prediction of speed could be found at other lags. For lapse probability, the effects of a lag were clearer, with the following optimal lags. Taking the temperature measured 0.5 minutes earlier than the last temperature assessment increased the magnitude of the regression coefficients for T_{chest} (1%), T_{finger} (4%), T_{wrist} (3%), and $DPG_{w\text{-}c}$ (6%). Taking the temperature measured 1 minute earlier than the last temperature assessment increased the magnitude of the regression coefficients for $DPG_{f\text{-}c}$ (9%) and $DPG_{f\text{-}w}$ (8%). These findings support the contention that assessment of momentary skin temperature may contribute to the prediction of subsequent performance. They also suggest that the time course of lapse probability fluctuations may lag behind the time course of response speed fluctuations, as has previously been reported in a different cognitive paradigm (West, 1999). Further research using temperature sensors with very short time constants in tasks of longer duration is needed to confirm this intriguing finding.

The finding that speed decreases and lapse increases with higher skin temperature might seem counterintuitive given the fact that circadian physiology research has shown that performance is usually minimal when temperature is low. However, these studies have focused almost exclusively on core body temperature. It has been described in studies looking into skin temperature, that under unrestricted conditions skin temperature follows a circadian rhythm that is inverse to that of core body temperature, with skin temperature being high when core body temperature is low (Van Marken Lichtenbelt et al., 2006). Furthermore, it was shown that core body temperature remains on a relatively stable plateau throughout the day, while skin temperature fluctuates more extensively (Van Marken Lichtenbelt et al., 2006).

As to the mechanisms involved in the predictive value of spontaneous fluctuations in skin temperature for spontaneous fluctuations in sustained attention performance, there is ample support that small changes in skin temperature modulate neuronal activity in brain areas that are involved in the regulation of vigilance (reviewed in Van Someren, 2000, 2003, 2004, 2006).

The results also show that we successfully created a brief stimulus reaction time task that has an overall lapse percentage of approximately 25% which is considerably higher than the lapse rate described in the PVT (Dinges & Powell, 1985; Van Dongen & Dinges, 2005), which has a lapse rate of approximately 4% (Loh et al., 2004). The majority of these lapses have to be attributed to fluctuations in information processing in the brain; only a very limited number of lapses may have resulted from missing the stimulus because it was presented during a blink. Combining the earlier findings of average blink rate (10.3 ± 3.1 blinks/min (Doughty, 2002)) and average time per blink (320 ms (Nakamura et al., 2008)), it can be estimated that the percentage of time spent with eyes closed during the task is 100*(10.3*320)/60000 = 5.5%. Due to the long interstimulus intervals of our task, the stimulus is present only about 0.26% of the time. The percentage of time that a stimulus is presented during a blink can thus be estimated to be only 5.5%*0.26% = about 0.01%.
We accomplished this high lapse rate by the exclusion of a millisecond timer that stays visible and may thus be seen at the end of a lapse, by lowering the contrast and shape difference between stimulus and background, and by relatively long interstimulus intervals. These adaptations may facilitate the study of brain mechanisms involved in lapses if a large number of 'lapse'-responses are required for analyses, as in functional magnetic resonance imaging (fMRI) studies (Drummond et al., 2005). Also the relatively long interstimulus intervals make our brief stimulus reaction time task suitable for fMRI-experiments, where long interstimulus intervals are needed to allow for completion of entire volume scans.

In conclusion, our results show that under circumstances that require sustained attention to weak stimuli while sitting under dimly lit conditions – as present also during e.g. nocturnal car driving or other process control situations – proximal temperature measurements may contribute significantly to the assessment of vigilance fluctuations. Of note, due to individual differences in their proximal temperature range, sustained recording is necessary for adequate classification of a single temperature readout within an individual's normal range, i.e. for mapping of actual temperatures onto the individual's normal range. The decile ratings account for 23% of the variance in response speed and or 11% of the variance in lapse rate. This reasonable reduction of 23% in the uncertainty about the response speed and 11% in the uncertainty about lapse rate may be further improved by combining skin temperature measurement with other indicators of vigilance that could be derived from the central nervous system, autonomic nervous system or behavior. Ultimately, combined assessment may improve the safety of process control in e.g. industry, surgery and driving through knowledge of the operator's vigilance level.

Acknowledgements

The authors would like to thank Paul Groot, Academic Medical Center of the University of Amsterdam, for his help with adaptation of the Psychomotor Vigilance Task. Funded by the Technology Foundation STW, Utrecht, Perspective NeuroSIPE Project 10738 and by the Netherlands Organization of Scientific Research (NWO), The Hague; VICI Innovation Grant 453-07-001 and Integrated Cognition Project Grant 051-04-010. Anonymous reviewers are acknowledged for suggesting important ancillary analyses.

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